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RIDE QUALITY IN A MULTIFACTOR ENVIRONMENT  
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**PREDICTION OF PASSENGER RIDE QUALITY IN A  
MULTIFACTOR ENVIRONMENT**

**By**

**Thomas K. Dempsey and Jack D. Leatherwood**

**September 1976**



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PREDICTION OF PASSENGER RIDE QUALITY IN A MULTIFACTOR ENVIRONMENT

Thomas K. Dempsey and Jack D. Leatherwood

Abstract of Paper Proposed for  
Eighty-Fourth Annual Convention of the American Psychological Association  
September 3-7, 1976  
Washington, DC

A model is being developed at NASA Langley Research Center which permits the understanding and prediction of passenger discomfort in a multifactor environment with particular emphasis upon combined noise and vibration. The model has general applicability to diverse transportation systems and provides a means of developing ride quality design criteria as well as a diagnostic tool for identifying the vibration and/or noise stimuli causing discomfort. The paper includes: (1) a review of the basic theoretical and mathematical computations associated with the model, (2) a discussion of methodological and criteria investigations for both the vertical and roll axes of vibration, (3) a description of within-axis masking of discomfort responses for the vertical axis, thereby allowing prediction of the total discomfort due to any random vertical vibration, (4) a discussion of initial data on between-axis masking, and (5) discussion of a study directed towards extension of the vibration model to the more general case of predicting ride quality in the combined noise and vibration environments.

## INTRODUCTION

Passenger comfort in public transportation vehicles such as aircraft, automobiles, and trains is strongly influenced by the combined effects of environmental factors such as vibrations, noise, temperature, etc. A model (ref. 1 and 2) has been developed at NASA Langley Research Center to provide a framework for accounting for the relative importance of various factors (vibratory and nonvibratory), as well as the interrelationship of these factors upon human discomfort responses. This paper summarizes the model and important methodological and criteria related results that have been obtained from a series of studies for development and application of the model.

The specific purposes of this paper are to: (1) describe the NASA ride quality model, (2) discuss the constant discomfort (or criteria) curves for the vertical and roll axes of vibration, as well as some of the methodological studies related to the experimental development and application of these criteria curves in the model, (3) present initial information regarding within-and between-axis masking of discomfort due to random vibration, and (4) describe the extension of this work to prediction of discomfort within a combined noise and vibration environment.

#### RIDE QUALITY MODEL: SCHEMATIC

The purpose of the ride quality model is to predict the total subjective discomfort associated with the ride environment of any transportation vehicle based upon appropriate empirical integration of the key factors known to influence ride quality. The ride quality model and associated environmental factors are illustrated in figure 1. Shown at the extreme left of the figure are the vehicle inputs consisting of noise and/or vibration. These inputs are modified by the vehicle transfer functions to give the output ride spectra experienced by the passengers. Theoretically, the output ride spectra is applied to the dashed box which contains the complex psychophysical relationships required to determine an interim discomfort scale. (The mathematics involved in these psychophysical relationships are discussed in a subsequent section.) The structure of the model is shown by the blocks in the dashed box. It is necessary to first determine the discomfort associated with each frequency component of a random ride and then to generate a set of constant discomfort curves for each axis of vibration. After the discomfort associated with individual frequencies is determined for each axis, it then remains to derive the empirical relationships governing how these discomfort components mask and/or summate both within and between axes when acting in combination. Once these effects have been determined, an interim comfort scale (as illustrated in figure 2) can be formulated. Further model corrections for the effects of noise, vibration duration, anxiety, etc., allow derivation of the final discomfort scale (or index). An actual hardware implementation of the model components of figure 1 is underway and will form the basis of a ride quality meter.

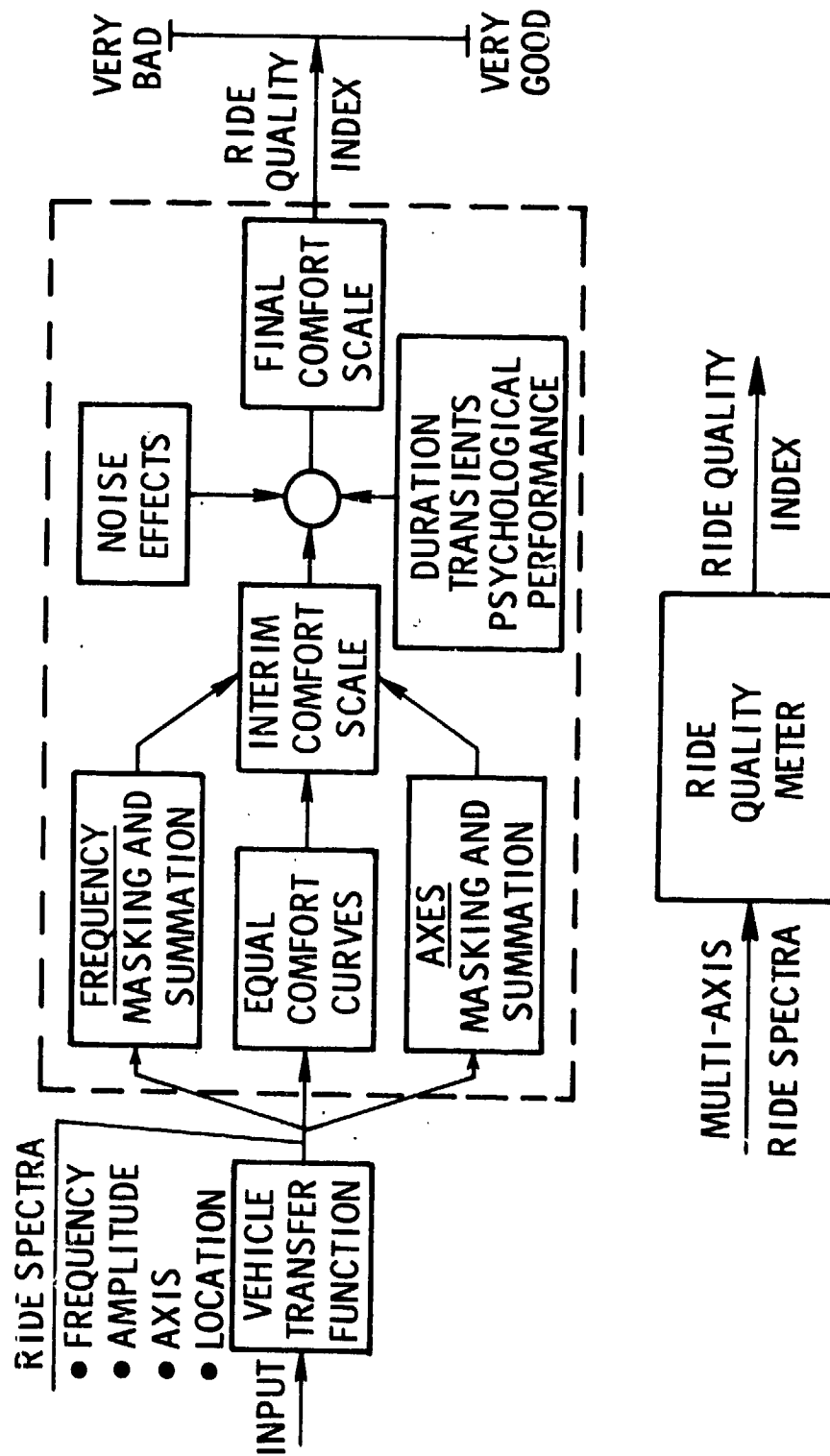


Figure 1

#### RIDE QUALITY MODEL: METER

The application of the ride quality model to new or existing vehicle designs is presented in figure 2. Estimated or measured inputs are applied to an experimental or estimated vehicle transfer function to give the ride environment at the passenger locations of the vehicle. This ride environment is provided as input to the ride quality meter (model), the output of which gives the passenger acceptability of the vehicle. If the acceptability level is sufficient, then the design or modification is complete, if not, then the model will diagnose the problem source so that a vehicle modification can be made. The process is then repeated until the required level of passenger acceptability is achieved. The actual information incorporated in the meter is partially supplied in subsequent sections and the remainder of the paper will represent topics of future investigations.

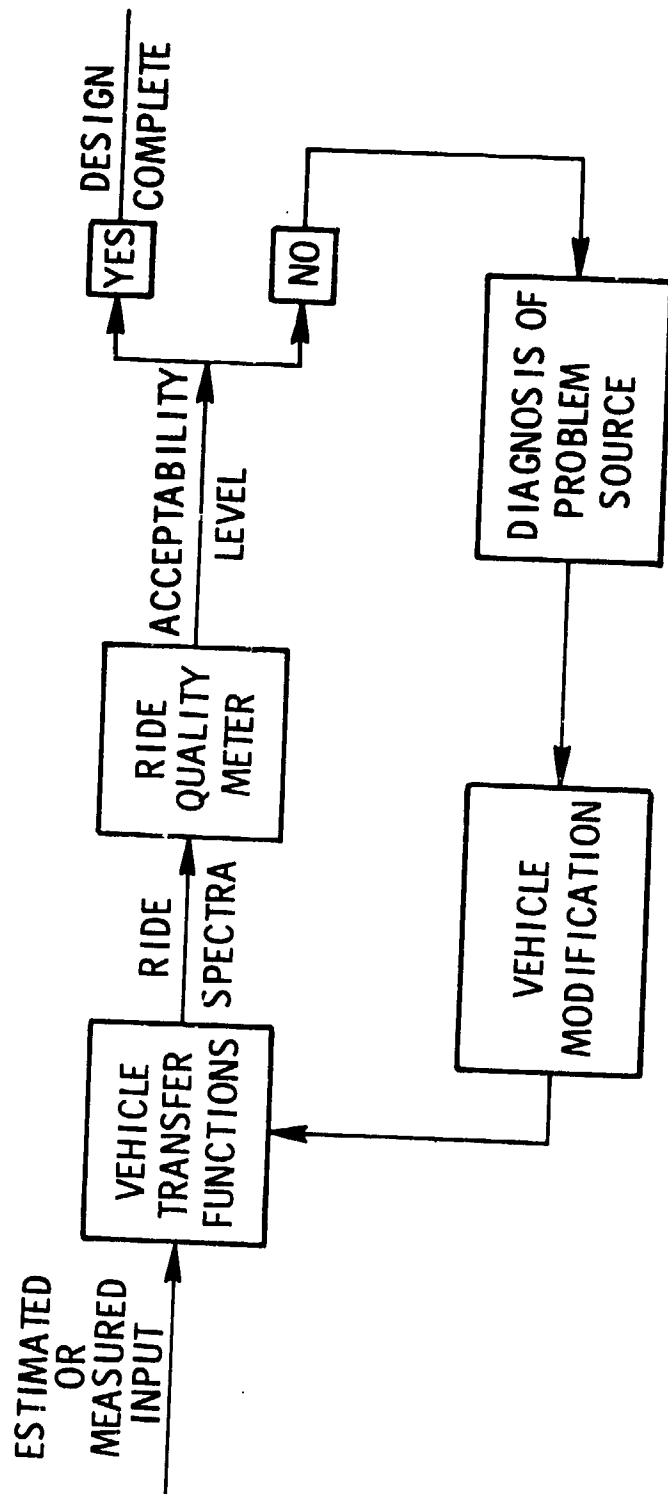


Figure 2



## RIDE QUALITY MODEL: MATHEMATICAL COMPUTATIONS

The mathematics associated with the psychophysical relationship between the various environmental factors and discomfort responses (i.e., the blocks within the dashed section of figure 2) are displayed in Table 1. These computations represent an extension of previous work in psychoacoustics (refs. 3-10) and vibration sensitivity (refs. 11-17). Formulas 1' to 3 apply to any axis of vibration. Formula 1 delineates the process for computing the total discomfort associated with one axis of vibration at a time, with formulas 2 and 3 describing the methods for derivation of masking/summation laws as well as integration of discomfort corrections for duration, onset, offset, and impulse. A composite discomfort is obtained in formula 4 which represents a relative weighting of each axis of vibration based on multiple regression analysis. The Final Discomfort Index is displayed in formula 5 which is based on inclusion of nonvibration discomfort corrections; the most important of which is noise.

TABLE 1.- MATHEMATICAL COMPUTATIONS OF RIDE QUALITY MODEL

Formula (1): Total Discomfort =  $DISC_{(TOTAL)} = DISC_{MAXIMUM} + F(\Sigma DISC - DISC_{MAXIMUM})$

Formula (2): Masking/Summation Factor =  $F = (DISC_{TOTAL} - DISC_{MAXIMUM}) / (\Sigma DISC - DISC_{MAXIMUM})$

Formula (3): Effective Discomfort =  $ED = DISC_{(TOTAL)} + DISC_{DURATION} + DISC_{ONSET} + DISC_{OFFSET} + DISC_{IMPULSE}$

Duration Correction<sup>a</sup>:  $DISC_{DURATION} = DISC_{(TOTAL, duration = t)} - DISC_{(TOTAL, duration = 10 \text{ sec})}$

Formula (4): Composite Discomfort =  $CD = \beta_v ED_{VERTICAL} + \beta_l ED_{LATERAL} + \beta_1 ED_{LONGITUDINAL} + \beta_r ED_{ROLL} + \beta_p ED_{PITCH}$

Formula (5): Final Discomfort Index =  $FDI = CD + DISC_{NOISE} + DISC_{TEMPERATURE} + DISC_{ANXIETY} \dots$

Noise Correction<sup>b</sup>:  $DISC_{NOISE} = DISC_{(TOTAL, ndB)} - DISC_{(TOTAL, ambient \text{ dB})}$

<sup>a</sup>The duration correction is displayed although similar analyses are applicable to onset, offset, and impulse.

<sup>b</sup>The noise correction is displayed although similar analyses are applicable to temperature, anxiety, etc.

### Experimental Apparatus

The apparatus used was the Langley Passenger Ride Quality Apparatus (PRQA). The PRQA is described briefly in this section and a detailed description can be obtained from references 18 and 19. The PRQA and associated programming control instrumentation are shown in the photographs of figure 3. Figure 3(a) shows the waiting room where subjects are instructed as to their participation in the experiment, the completion of questionnaires, etc. Figures 3(b) and 3(c) are photographs of the exterior of PRQA, and it should be noted that the actual mechanisms which drive the simulator are located beneath the pictured floor. Shown in figure 3(d) is a model of the PRQA indicating the supports, actuators, and restraints of the three-axis drive system. The control console is shown in figure 3(e) and is located at the same level as the simulator to allow the console control operator to constantly monitor subjects within the simulator. An interior view of PRQA fitted with tourist-class aircraft seats is shown in figure 3(f). Additional interior views (with front or back panels removed) are displayed in figures 3(g), 3(h), and 3(i). Octave band noises were produced within the PRQA cabin by applying the output of a random noise generator to a selectable octave filter set and, thence, through appropriate amplifiers into the cabin speaker.



Figure 3

## VERTICAL AXIS: METHODOLOGICAL PROBLEMS

In order to derive vertical axis criteria with general applicability to diverse transportation vehicles, it was necessary to consider several problems of a methodological nature (ref. 20-23) which included: (1) a determination of the psychophysical relationship between comfort responses and vibration stimuli, (2) an assessment of the level of sophistication required in the measurement and analysis of vibration ride spectra data for accurate prediction of passenger discomfort, (3) a determination of the relative importance of seat and floor vibration in the selection of a measurement and criteria specification location, and (4) a determination of the effects of practice by the subjects on evaluation of vibration. Each of these methodological areas are discussed in subsequent sections.

### Psychophysical Laws

An experimental study (ref. 23) in which subjects performed magnitude estimations of sinusoidal vibration on PPJA was used to: (1) determine in a systematic manner the psychophysical relationship (linear, power, exponential, and logarithmic) governing human assessment of the intensity and discomfort due to whole-body vertical vibration, and (2) determine if intensity and discomfort responses differ from one another.

Figure 4 displays magnitude estimations of discomfort and intensity as a function of peak acceleration level for 17 Hz. These results and other statistical analyses indicated that (1) a linear law should be selected for description of the relationship between subjective ratings of intensity or discomfort and vibration level, and (2) there was a significant difference between the sensations of intensity and discomfort for three of the ten frequencies investigated. This implies that caution should be used when applying results from vibration intensity studies to the problem of developing discomfort response criteria.

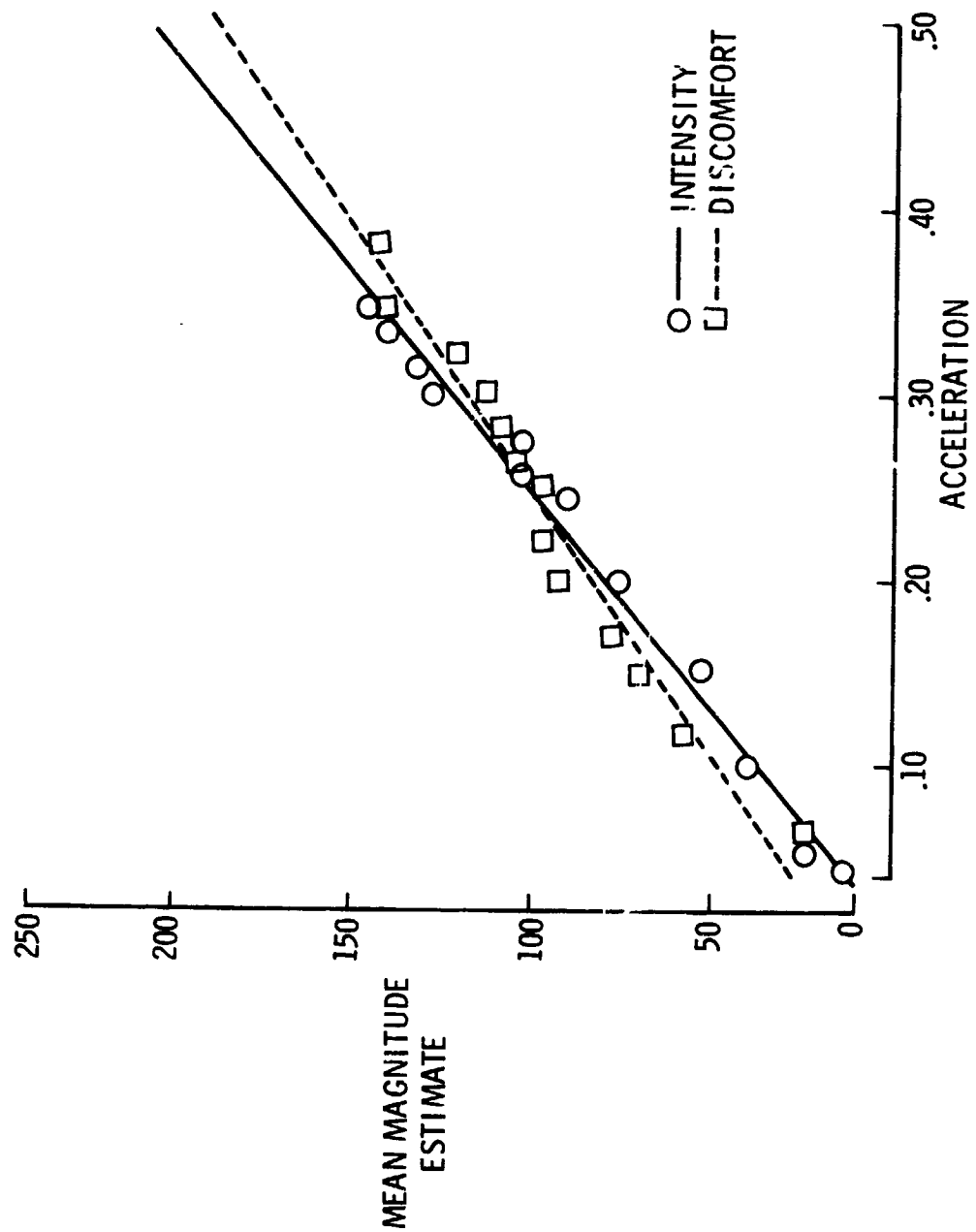


Figure 4

### Spectrum Analysis

Prior to conducting specific and detailed experiments for development of the model, information was needed regarding the type of ride data analysis required for the prediction of discomfort. The problem is to ascertain whether the prediction of passenger discomfort can be based on an overall measure obtained by frequency averaging (e.g.,  $g_{rms}$ ) or if the information is needed on the frequency content of the vibration spectrum.

A study (ref. 22) was completed in which subjects evaluated the discomfort of various sinusoidal vibrations (of various peak acceleration levels) using a unipolar nine-point continuous scale of discomfort. An analysis of variance indicated there was a significant interaction between acceleration level and frequency. Figure 5 graphically displays this interaction. The figure shows the mean discomfort ratings as a function of frequency for five levels of seat acceleration. Note that the mean discomfort ratings vary with frequency for each acceleration level and that at each frequency the ratings are dependent upon acceleration level. Thus, in order to determine the degree of discomfort, it is necessary to have knowledge of both the frequency and acceleration content of a ride. The case where many frequencies are present simultaneously requires further analysis and will be discussed in a later section.

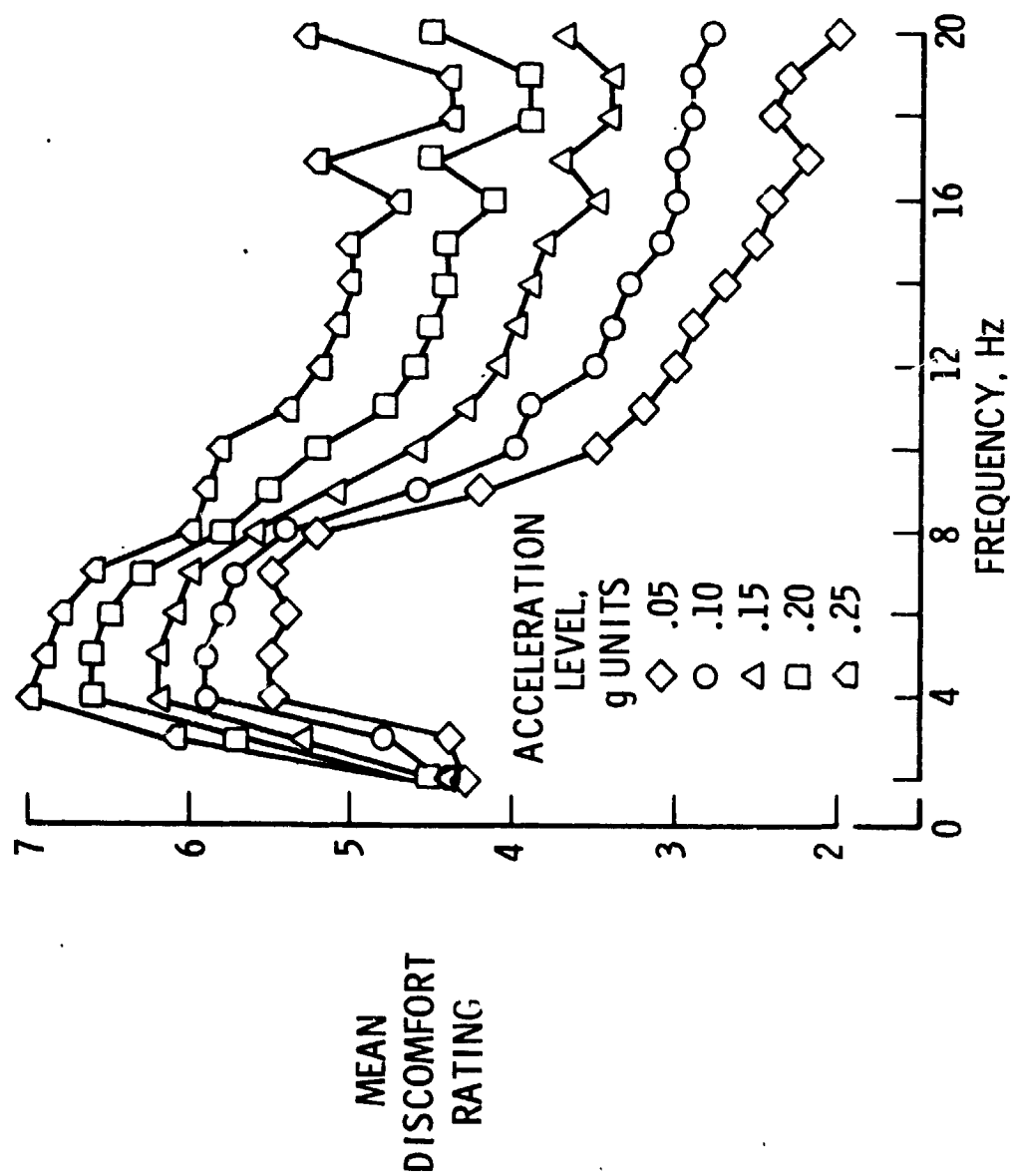


Figure 5



## Seat-Floor Considerations

The question frequently arises as to what location should be used for specification of ride quality criteria and for measuring the vibration environment. Most previous investigations (e.g., refs. 24-27) have developed comfort criteria based upon floor measurements (many used rigid seats). Consequently, seat compliance (ref. 20) has not been accounted for in criteria development. This section discusses the relative contribution of vibrations at the seat and floor (when the vibrations are simultaneously experienced) to the total discomfort of a passenger, and concludes with a recommendation for locating measurement packages and specifying criteria. The discussion herein will be concerned with tourist-class aircraft seats although the results have been shown to apply to first-class aircraft seats as well as bus seats (ref. 22).

Typical results of this study are displayed in figure 6. The figure shows the mean discomfort ratings as a function of floor and seat acceleration levels for three vertical sinusoidal frequencies. Particular note should be taken of the parallel trends of each pair of solid and dashed curves. The average correlation coefficient between measured seat and floor accelerations was 0.87 indicating these measures are not independent and, consequently, cannot be used to compute weighting factors for the relative contribution to discomfort of the two measures. In addition, t-test comparisons between the floor and seat correlation coefficients of discomfort response with acceleration indicated no significant difference in the contribution of vibration at the floor or at the seat to the total discomfort of a passenger. This means that either location will give equal predictability of discomfort responses. For simplicity and convenience, it is therefore recommended that the floor be used as the location for measurement and criteria specification.

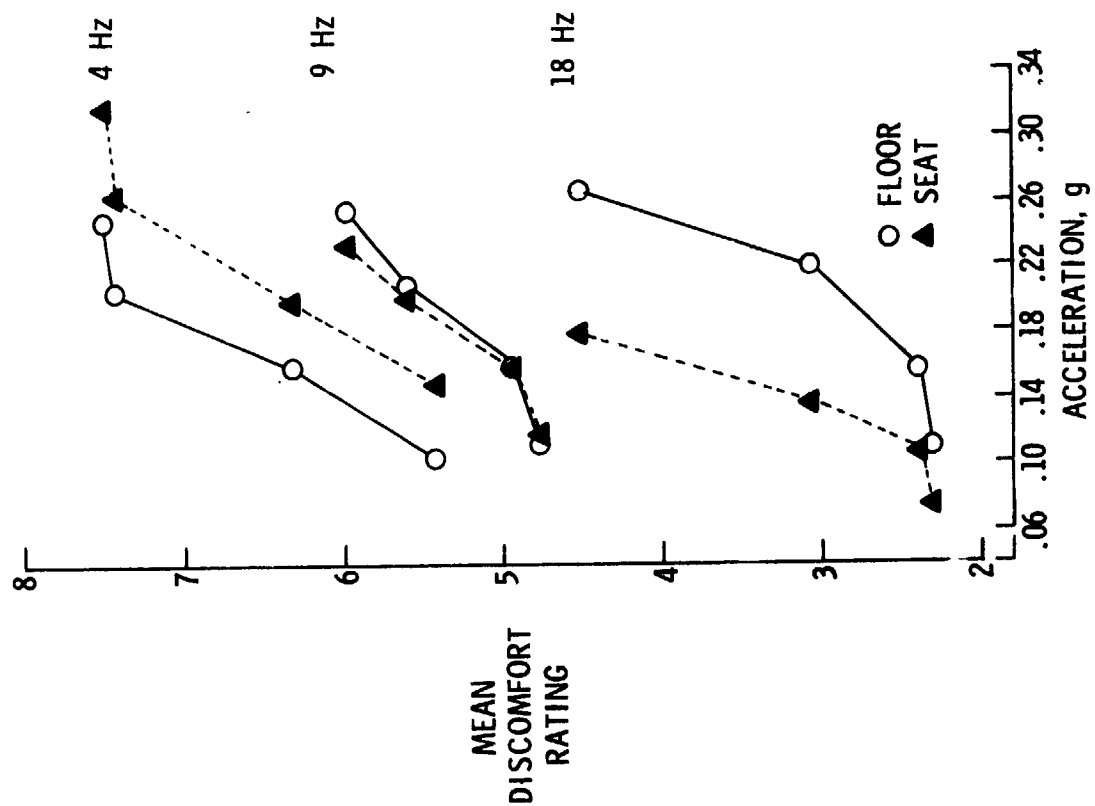


Figure 6

### Practice Effects

Prior to extensive investigation of the influence of various factors (e.g., exposure duration, noise, etc.) on discomfort, it was necessary to determine whether to use "practiced" or "naive" (i.e., untrained) subjects. Figure 7 (from ref. 22) displays discomfort ratings as a function of subsequent sessions of vibration. This figure indicates no systematic effect of practice upon subsequent discomfort responses. The initial decrease and subsequent increase of discomfort ratings across sessions can, in large part, be attributed to a single group of subjects. Furthermore, the demographic factors of age, weight, and sex did not contribute significantly to the explanation of discomfort response variation.

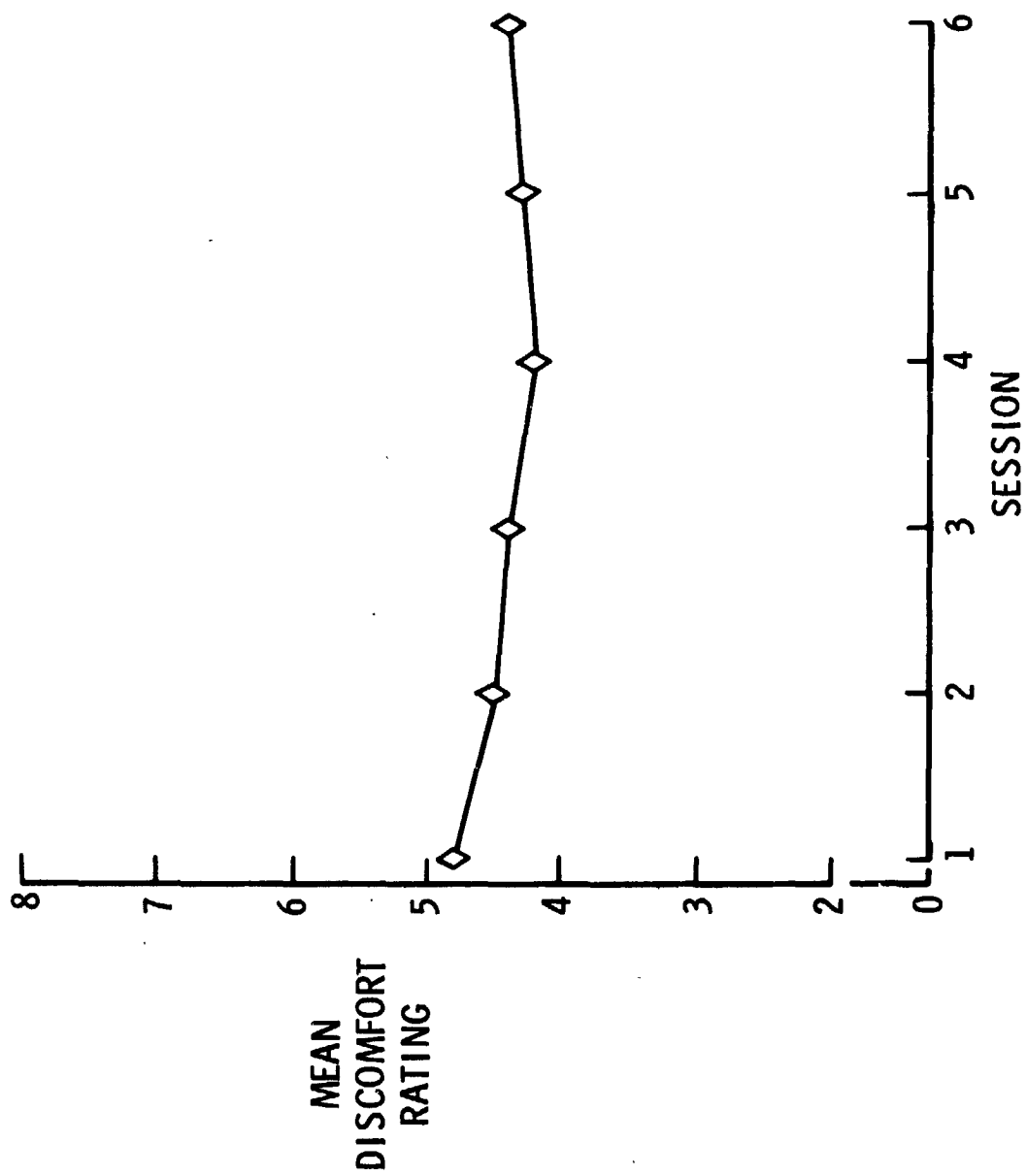


Figure 7

#### VERTICAL CRITERIA: CONSTANT DISCOMFORT CURVES

A series of three studies (refs. 28 and 29) using 186 subjects was conducted to supply the necessary information for formulas 1 and 2 in Table I. The first two studies were directed at generation of constant discomfort curves and the third at a determination of the masking/summation relationships. The first study used a modified method of limits and was directed at the determination of the acceleration levels at different frequencies that produce identical discomfort. Data from this study (and that of a previous investigation, ref. 20) were used to anchor the discomfort magnitude estimations at each frequency relative to the discomfort threshold. Using these anchor points, the discomfort magnitude estimates as a function of acceleration level were determined for each frequency and provided the basis for generating the set of constant discomfort curves presented in figure 8. The individual curves of figure 8 indicate the acceleration level of a sinusoidal vibration required at each frequency to produce a constant level of discomfort. This figure shows constant discomfort curves ranging from a value of one ( $DISC = 1$ ), which is approximately the discomfort threshold, to values as high as  $DISC = 12$  corresponding to a very high level of discomfort.

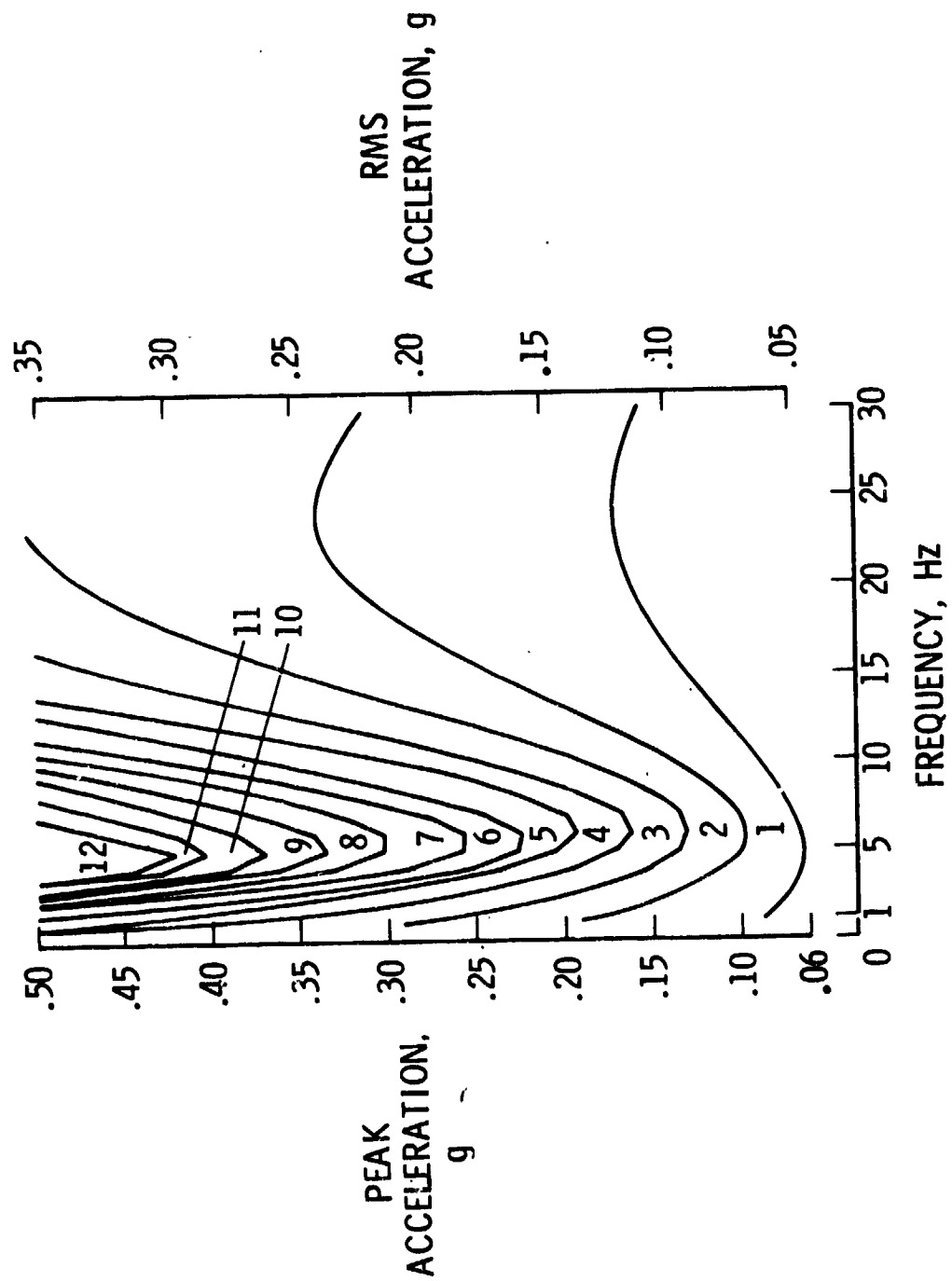


Figure 8

#### Vertical Criteria: Masking/Summation

The third study of the series addressed the question of how the total discomfort of a ride is affected when different frequency components are combined. Such knowledge can be derived from formulas 1 and 2 and are required for application of this information to actual transportation vehicle ride environments. The studies reviewed in the previous section provided the necessary information for computation of formula 1, except for F, the masking factor. The derivation of F as a function of bandwidth, center frequency, and acceleration level of vibration was the purpose of the third study. Logically, the value of F in formula 1 should approach unity if the discomfort associated with each successive band (1 Hz bandwidth) of the spectrum is additive. Alternately, as the value of F approaches zero, the 1 Hz bandwidth component that contributes maximum discomfort becomes the sole predictor of discomfort for the random vibration. In other words, for this latter case, the frequency contributing maximum discomfort can be conceived of as masking the discomfort associated with other frequency components of the random vibration.

Figure 9 displays the F value (masking factor) for 2, 5, and 10 Hz bandwidth random vibrations as a function of rms acceleration levels of the vibration. The figure clearly displays that there is a greater masking effect for smaller bandwidths of vibration, and that these effects increase as a function of rms acceleration level for each bandwidth. There were no systematic trends for F as a function of center frequency for any of the bandwidths. Consequently, selection of F (masking factor) for computation of the total discomfort of a random vibration (affect of different frequencies in combination) needs only to consider the bandwidth and total rms acceleration level of the random vibration.

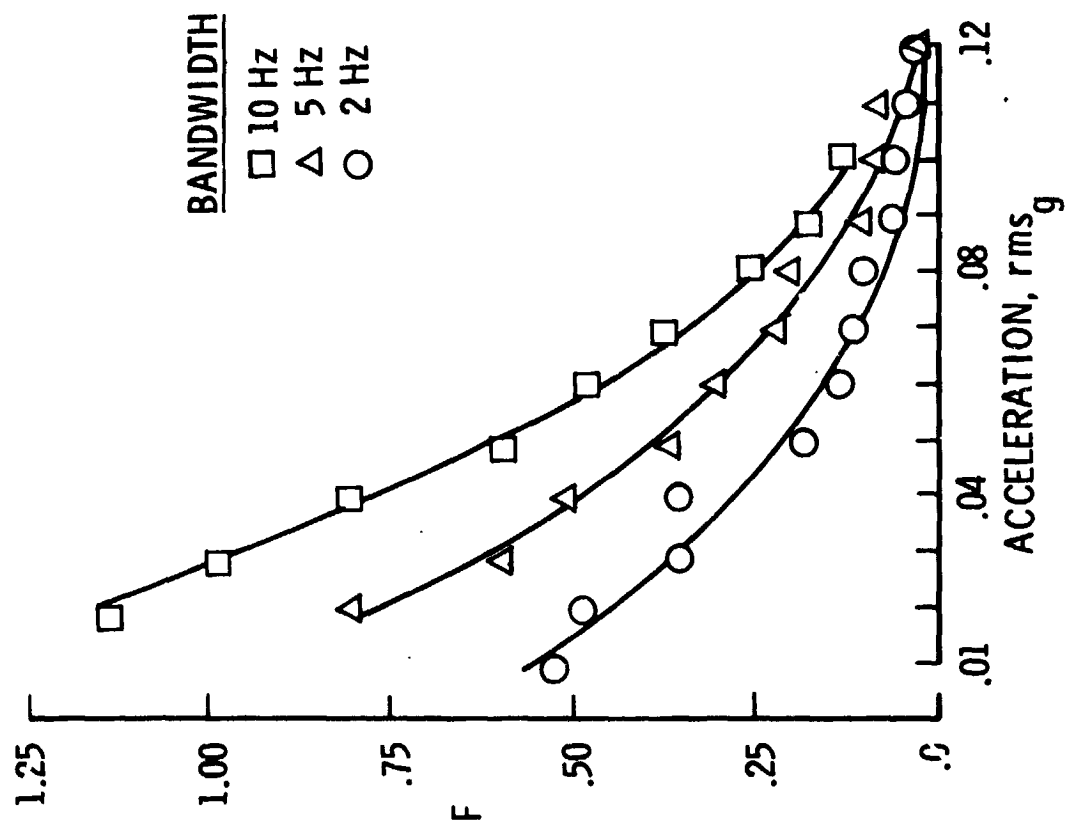


Figure 9



## ROLL AXIS: METHODOLOGICAL PROBLEMS

Analogous to vertical axis methodological problems, there were several issues specifically related to the roll axis that needed solutions prior to the development of roll criteria. An experimental investigation (ref. 30) was conducted on PRQA to: (1) explore the effect upon human discomfort of roll vibrations and in particular the effects of frequency and acceleration; and (2) determine the importance of distance from the axis of rotation of a seated subject. These topics are discussed in successive sections.

### Roll Vibration: Frequency and Acceleration Level

Prior to the development of criteria for the roll axis of vibration, it was not apparent just what role these angular motions played in ride quality. Consequently, a study was conducted in which a total of 72 subjects were exposed to various roll vibrations. The factors parametrically combined for investigation were roll frequency (1 through 4 Hz), roll acceleration level ( $0.48$  to  $2.88 \text{ rad/sec}^2$ ), and seat location (window, center, and aisle seats). An analysis of variance applied to the data indicated that the effects of roll acceleration, roll frequency, as well as their interaction were significant. Figure 10 displays this interaction. There are several implications that can be derived from these analyses. First, the curves of figure 10 demonstrate a basic linearly increasing trend of discomfort response with roll acceleration, which is in accord with the previous discussion regarding the selection of a linear psychophysical law for vertical vibration. Secondly, the effect of frequency is apparent, especially at the higher levels of roll acceleration. Consequently, the prediction of discomfort due to the roll component of motion will require knowledge of roll frequency, roll acceleration level, and their interaction.

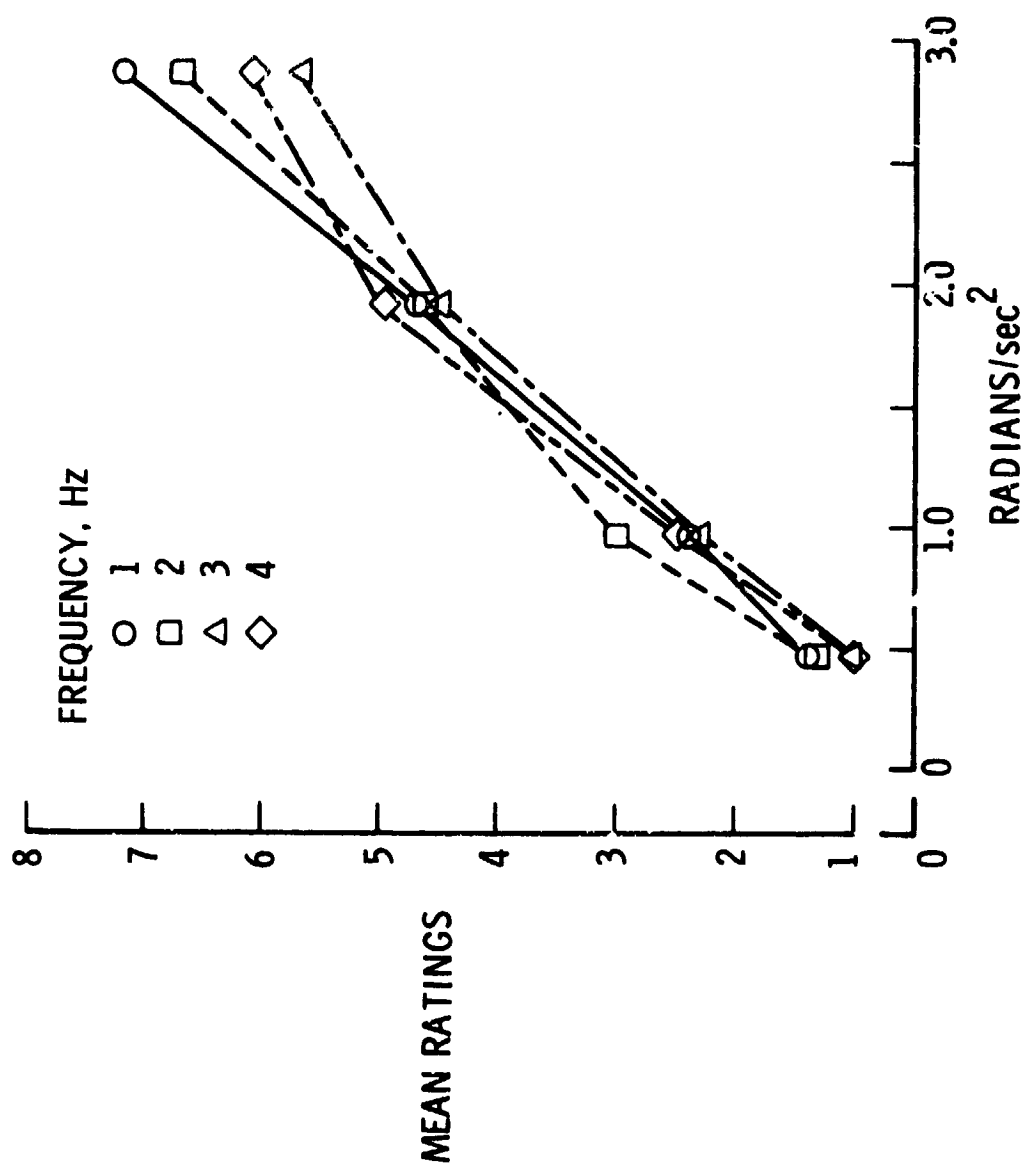


Figure 10

#### Roll Vibration: Seat Location

The analysis of variance indicated that the effect of seat location on subjective evaluations was not significant for the particular seat arrangement and roll axis used in this study. The overall effect of seat location is illustrated in figure 11 which shows the mean ratings (averaged over roll frequency) for each seat location as a function of roll acceleration level. Although this graph shows some spread between the points (for each roll acceleration level) corresponding to each seat location, these differences are not statistically significant. However, these results must be qualified by the fact that many vehicles are configured differently than the test cabin used in this study, and consequently the passengers may be located at different distances from the axis as well as experience different levels of roll acceleration. Thus, these results are not intended to be construed as general results but are restricted to the particular cabin geometry and roll vibrations studied herein. It is believed, however, that the configuration and the roll vibration environment are representative of many existing transport vehicles.

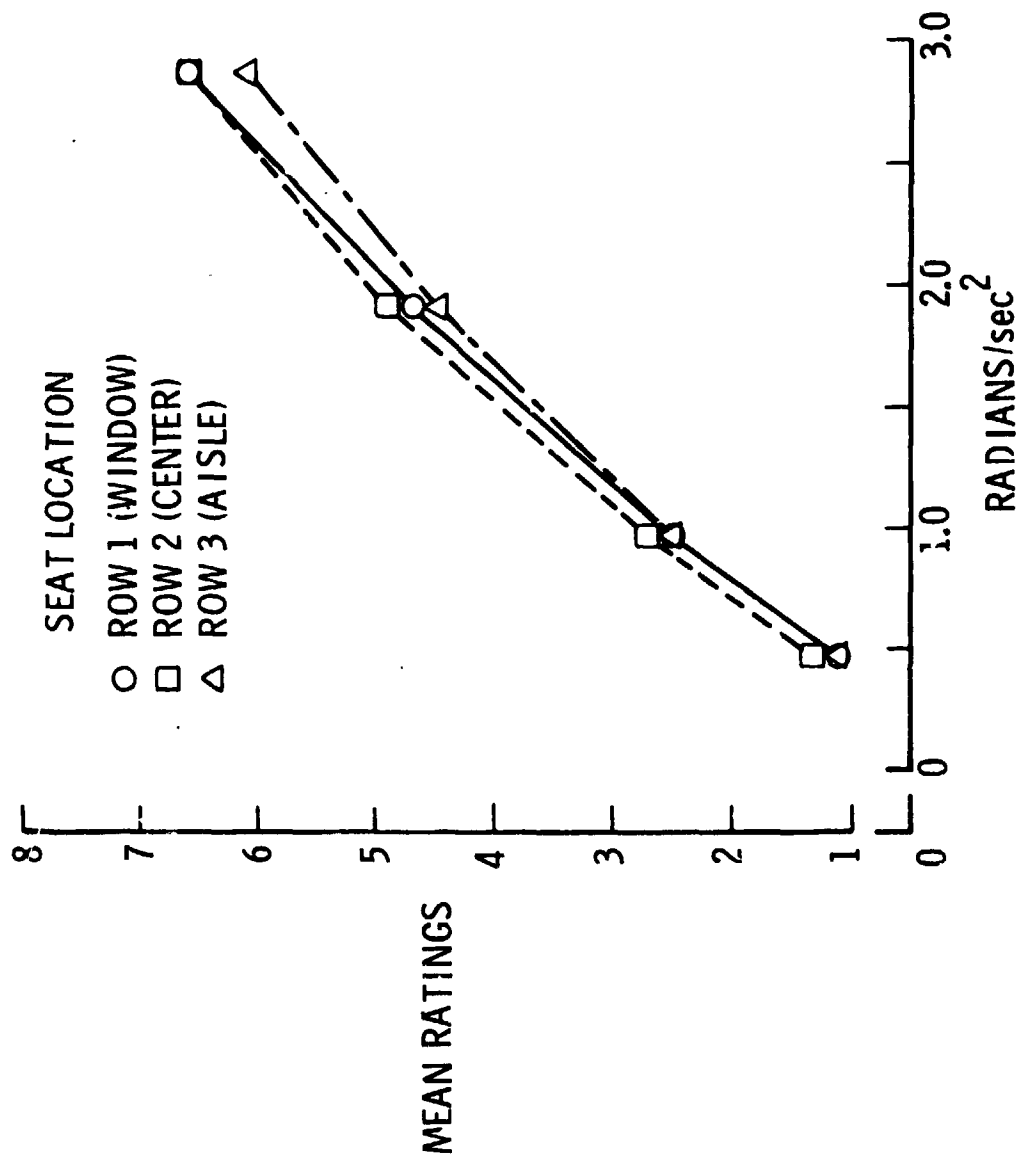


Figure 11

### Roll Criteria: Constant Discomfort Curves

A study using 96 subjects was conducted to determine the total discomfort of any random roll vibration using formula 1. Prior to conducting the experimental procedures for the investigation of roll vibration analogous to those for vertical vibration, the discomfort of the two axes was equated. For example, it was determined what radians/sec<sup>2</sup> of a 2 Hz sinusoidal roll vibration equaled at peak acceleration level of 0.15 of 9 Hz vertical vibration. Consequently, the discomfort units (DISC values) for the two axes are similar.

Figure 12 displays the constant discomfort curves for roll vibration. Each curve of the figure indicates the roll acceleration level of a sinusoidal vibration required at each frequency to produce a constant level of discomfort. Additional implications of the figure are: (1) the lower frequencies appear to provide the greatest discomfort, (2) the maximum discomfort for sinusoidal roll vibrations is less than for sinusoidal vertical vibration, and (3) the comparison of roll masking/summation with that for vertical will become apparent in subsequent report of this data.

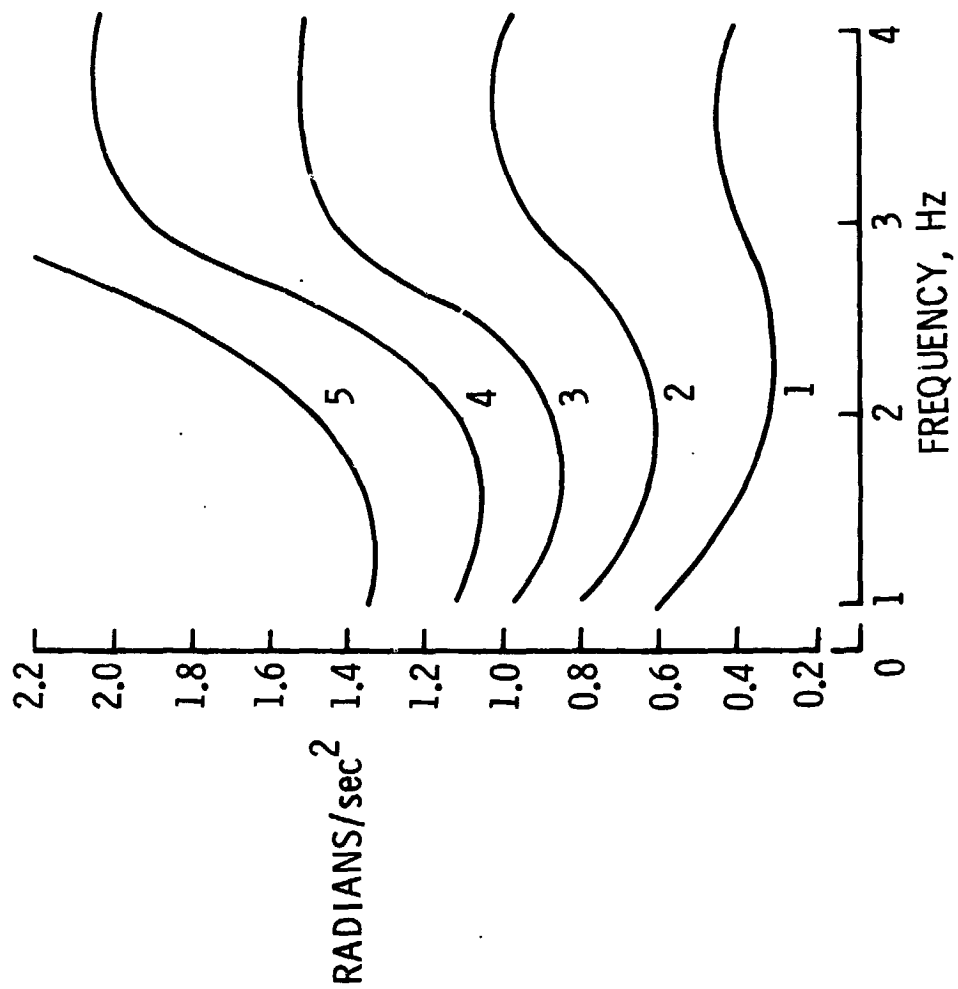


Figure 12

#### COMBINED AXIS: MASKING/SUMMATION

The results reported earlier in this paper dealt exclusively with a single axis of vibration and consequently the topic of within axis masking. An initial study was conducted (ref. 31) to explore between axis masking. The study exposed subjects to combined vertical and lateral vibrations at input frequencies ranging from 1 to 20 Hz for both axes. All acceleration levels were equal to a peak g of 0.15. Figure 13 shows the mean discomfort ratings (based upon a nine-point unipolar discomfort scale) of the subjects as a function of lateral input frequency with added vertical input frequency as a parameter. The major implication of the figure is that lateral vibrations may tend to effectively mask the presence of vertical vibrations at comparable acceleration levels, especially at lower frequencies of lateral input. Additional data analyses of the study indicated a somewhat complex relationship (interaction) exists between acceleration and frequency of the two axes. Further testing on PRQA and in the field (e.g., train, rapid transit systems, etc.) needs to be completed in order to finalize information in this area. A major problem for the use of field data in the ride quality model of this paper is the lack of transformations between the data of different subjective scales. The authors currently have a study being conducted which is directed at this problem.

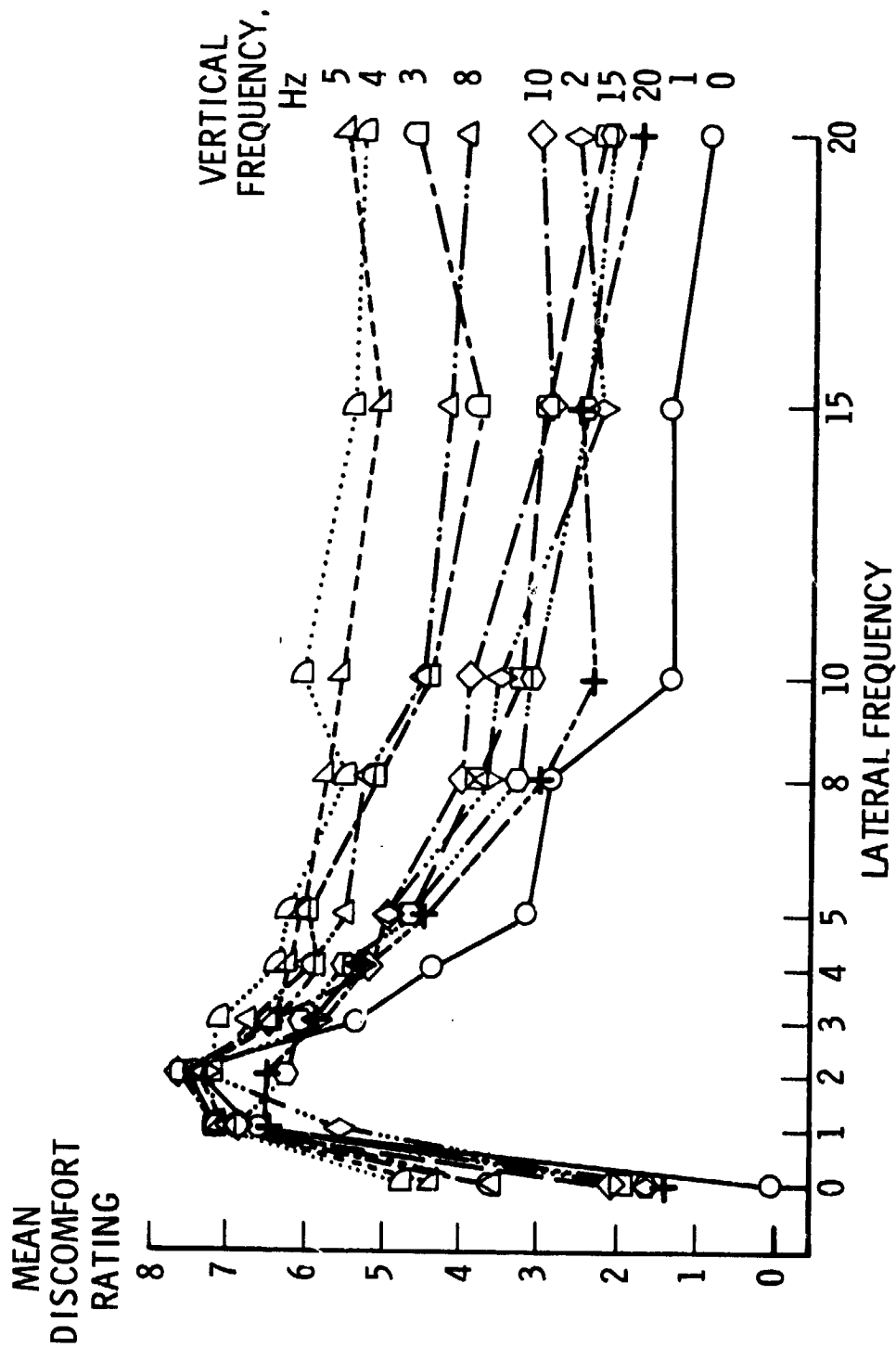


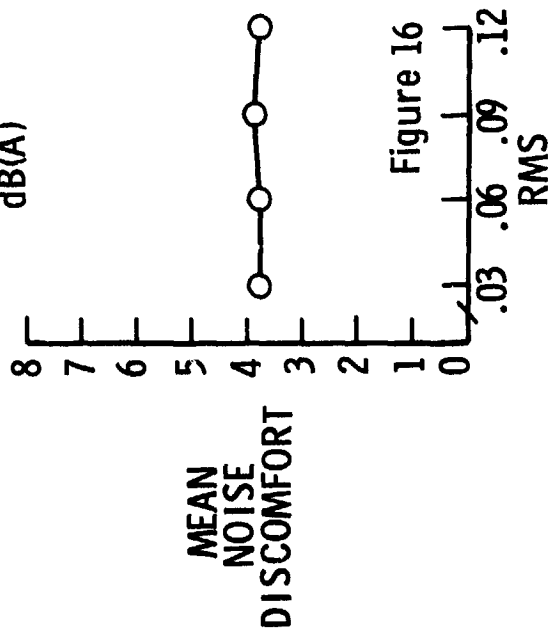
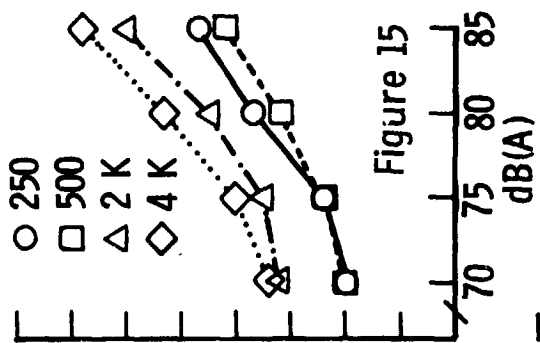
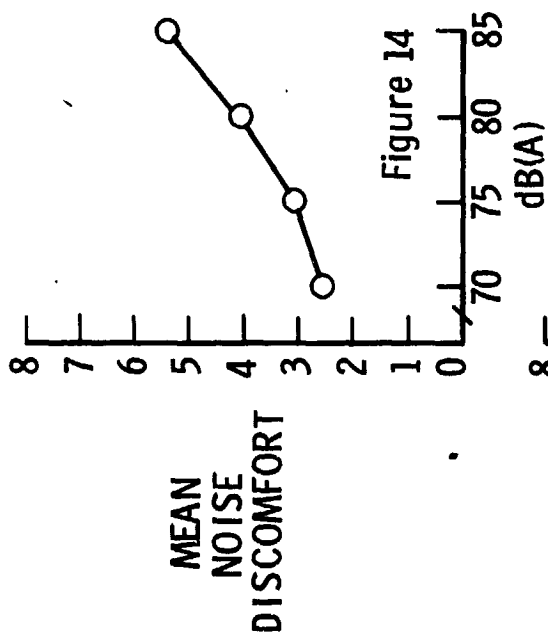
Figure 13



## RIDE QUALITY: COMBINED ENVIRONMENTS

The studies reported on earlier in this paper have dealt exclusively with the influence of vibratory factors on ride quality. This section addresses the effect of a combined noise and vibration environment on passenger discomfort. Prior to the development of noise and vibration criteria for ride quality, which could be either composite or separate criteria (either hierarchical or successive in nature), several problems of a methodological nature must be considered. These problems were addressed by an initial study (ref. 32) and included: (1) a determination of the subject's ability to separate noise and vibration as contributors to discomfort, (2) an assessment of the physical measures of noise and vibration that optimize ride quality prediction in this type of multifactor environment, and (3) a determination of the relative contribution of noise and vibration to passenger ride quality. The study required subjects using category scales to rate noise discomfort, vibration discomfort, both noise and vibration discomfort, and overall discomfort in an effort to evaluate parametric arrangements of noise and vibration. The noise stimuli were composed of octave frequency bands centered at 125, 250, 2,000, and 4,000 Hz, each presented at 70, 75, 80, and 85 dB(A). The vertical vibration stimuli were 5 Hz bandwidth random vibrations centered at 3, 5, 7, and 9 Hz, each presented at 0.03, 0.06, 0.09, and 0.12 grms.

Typical results of the study are presented in figures 14-17 (additional data can be obtained from ref. 17). The figures display the mean noise discomfort that occurred as a function of the major factors investigated. Implications of these data and other analyses were: (1) information of the intensity level and spectrum content of both noise and vibration is needed for the accurate prediction of ride quality, (2) from a practical point of view, subjects can separate the influence of noise and vibration measures on



different discomfort scales, (3) the most comprehensive prediction of discomfort in a noise-vibration environment appears to result from the collection of subjective responses on separate, but simultaneous, noise discomfort and vibration discomfort scales, (4) initial results indicate that vibration measures account for as great as four times the amount of explained variance as do noise measures. The next major study in this area will be to derive a discomfort noise correction consistent with the model.

### CONCLUDING REMARKS

This paper has presented a comprehensive model for the development of passenger ride quality criteria. Results from a series of studies have been presented which contribute to the development of such a model as well as to a more comprehensive understanding of human comfort response to vibration. The major points of interest are summarized as follows:

1. The theoretical and mathematical steps necessary for computation of passenger discomfort associated with multiaxis vibration and nonvibratory factors were outlined in a model format.
2. The series of methodological studies necessary for development of vertical criteria was outlined and provided the following results:
  - Caution should be used in applying results from vibration intensity evaluation studies to the problem of human discomfort response.
  - A linear relationship can be used to describe the psychophysical law governing human response to vertical vibration.
  - In order to accurately assess the level of discomfort of a vibration, knowledge of both frequency and acceleration amplitude is required.
  - The floor location in a vehicle can be used as the point for making vibration measurements and specifying ride quality criteria. If it is desired to specify criteria at the seat, then the floor criteria can be corrected by applying the seat transfer function to the floor input.
  - Either practiced or naive subjects can be used equally well for the investigation of human response to vibration.

3. A set of equal discomfort curves for vertical vibration were developed. These results, in addition to being necessary for formula 1, for model development, provide detailed information on human discomfort response to increases of acceleration level for each frequency investigated. More importantly, the results provide a method for adding the discomfort associated with separate frequencies for a total typification of the discomfort of a random spectrum of vertical vibration.
4. The methodological study necessary for development of roll axis criteria was discussed and the following conclusions derived:
  - The prediction of passenger discomfort due to the roll vibration component requires knowledge of roll frequency, roll acceleration, and their interaction.
  - Subjective responses varied linearly with roll acceleration.
  - For the particular seat arrangement of the present study, the distance of the seat from the axis of rotation was not important.
5. A set of equal discomfort curves for roll vibration were developed. Initial comparison of these curves to those for vertical vibration was discussed.
6. Between axis masking/summation does occur and is needed for final model development.
7. A study of human discomfort response to combined noise and vibration indicated the following:
  - Information of the intensity level and spectrum content of both noise and vibration is needed for the accurate prediction of ride quality.
  - From a practical point of view, subjects can separate the influence of noise and vibration measures on different discomfort scales.

- The most comprehensive prediction of discomfort in a noise-vibration environment appears to result from the collection of subjective responses on separate but simultaneous noise discomfort and vibration discomfort scales.
- Initial results indicate that vibration measures account for as great as four times the amount of explained variance as do noise measures.

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